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ENHANCED IGNITION FOR I.C. ENGINES WITH PREMIXED CHARGE

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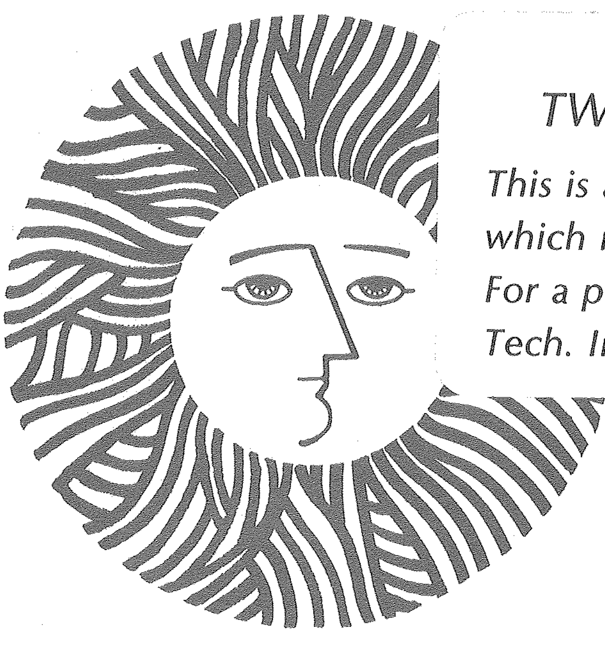

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ABSTRACT

The development of lean charge, fast burn engines depends crucially on enhanced ignition, since one can obtain thereby proper means for increasing the rate of burn in mixtures characterized notoriously by low normal burning speeds. Enhanced ignition involves not only high energies and long duration of ignition, but also a wide dispersion of its sources, so that combustion is carried out at as many sites throughout the charge as possible. Upon this premise, various ignition systems for I.C. engines, operating with premixed charge, are reviewed.

The systems are grouped within the following categories: (1) high energy spark plugs; (2) plasma jet igniters; (3) photochemical, laser, and microwave ignition concepts; (4) torch cells; (5) divided chamber stratified charge engines; (6) flame jet igniters; (7) combustion jet ignition concepts; (8) EGR ignition system. The first three derive the power from electrical energy, the rest are powered by exothermic chemical reactions at a significantly lower, practically negligible, fuel consumption.

The review emphasizes the concept of staging the processes of initiation and propagation of combustion. Relative positions of various ignition systems is expressed on the plane of relative energies (the ratio of energy consumed by the ignition system, or contained in a pre-chamber, to that of the compressed charge in the main chamber) and relative volumes (the ratio of the volume of the pre-chamber to that of the compressed charge).

In principle, ignition systems for engines operating with premixed charge lie on the half-plane of relative energies below one, between 10^{-5} for standard spark plugs to 10^{-1} for divided chamber stratified charge engines, while their relative volumes extend from 0 for spark igniters to 0.2 for stratified charge engines. This suggests that proper compartmentization of the combustion process may lead to significant improvements in both pollution emissions from the cylinder and specific fuel consumption of I.C. engines.

INTRODUCTION

One of the most attractive features of the current trend in the evolution of S.I. engines is the concept of lean charge associated with fast burn. The achievement of such conditions requires enhanced ignition, a development involving not only an increase in the energy and duration of the ignition process, but also an augmentation in the dispersion of ignition sources. This is due to the fact that high rates of burning in a lean charge, characterized by low flame velocities, can be attained only by having the combustion initiated at a multitude of sites distributed throughout the mixture. In practice such distribution can be accomplished either by having the fresh charge pass by a single ignition source or, what obviously is much better, having it seeded with ignition sources throughout its bulk.

With this in mind, reviewing the great variety of systems and concepts known today for enhanced ignition appeared to us worthwhile, and hence this paper.

The devices covered by the review are grouped within the following categories:

1. High Energy Spark Plugs
2. Plasma Jet Igniters
3. Photochemical, Laser, and Microwave Ignition Concepts
4. Torch Cells
5. Divided Chamber Stratified Charge Engines
6. Flame Jet Igniters
7. Combustion Jet Ignition Concepts
8. EGR Ignition System

Here by concepts reference is made to means which are considered to be of no practical importance in actual engine application but which are of definite value for research and development, especially in establishing the effects of the location, intensity and other essential properties of various ignition sources on the combustion process they initiate. The inclusion of these devices stems from our intent to provide information on the ways and means that could be useful in the development of enhanced ignition systems in the future, rather than just on the state of the art existing today. Broadly, the systems -- devices of practical significance -- consist of two groups: electrical and chemical. Within each, the categories are reviewed in a sequence corresponding to the status of their development.

HIGH ENERGY SPARK PLUGS

The fact that the energy required by electric sparks for successful ignition is at a minimum for stoichiometric mixtures is well established [1]. The process of spark ignition depends on many parameters such as arc energy, peak voltage, duration of discharge, geometry of the spark gap, and its location relative to the particular geometry of the compressed charge [2-8]. The interest in the development of spark igniters for lean mixtures provided an incentive for detailed studies of the mechanism of spark ignition, conducted over the recent years at the University of Stuttgart in cooperation with the Research Division of Daimler-Benz [9-11].

At the same time new ideas were developed for boosting power supply in a controllable manner to high energy spark plugs [12,13]. These are referred to as Supplementary Secondary Energy (SSE) systems, and their salient features are depicted in Fig. 1. The basic principle here is to provide a negative bias of an order of 3 KV to the secondary coil in the pulse transformer (Fig. 1a). This results in an increased peak power, as well as a significant prolongation of the discharge (Fig. 1b).

All these developments are based on the premise that by proper control of the manner in which the plasma is generated by the discharge, leading in particular to the prolongation of its duration, more unburned mixtures can be exposed to it, an effect that can be greatly enhanced by the use of squish whereby a significant amount of mixture can be caused to pass by the gap and be mixed with plasma, generating thereby in effect a system of distributed ignition sources.

Tests performed on single as well as multi-cylinder engines demonstrated that increasing the gap width, its projection, and the duration of the spark, can definitely extend the lean missfire limit (LML). Using high energy spark plugs with arc duration prolonged to 5 msec, the air fuel ratio corresponding to LML could be increased by 10 to 15 percent while the tolerance to exhaust gas recirculation (EGR) could be doubled [(5)]. At the same time, however, the emissions of especially HC and CO were not sufficiently reduced to meet the statutory requirements. Thus, it appeared that while the initiation of the combustion process was enhanced, the burning of the mixture had still to rely by far on the propagation of a single flame front that, in a mixture diluted by excess air and/or exhaust gas, was too slow to consume the whole charge within the allowable time. It is quite likely that the most important factor in this respect could have been the bulk quenching studied by Smith, Westbrook and Sawyer [(14)] and Quadar [(15)].

The use of high energy spark plugs is, of course, most practical. In this connection it should be noted that in its most rudimentary form, one associated simply with the use of two conventional spark plugs instead of one, this principle has been successfully adopted in a number of engines, see e.g. Figs. 2 and 3.

PLASMA JET IGNITERS

In these devices the spark discharge is confined to a recessed cavity provided with a discharge orifice, while the electric power supply is augmented by the addition of a condenser that discharges at a relatively low voltage and high current through the spark generated in a conventional manner by a high voltage, low current ignition system. A schematic diagram of a plasma jet igniter and its electric power supply is shown in Fig. 4. The circuit consists of a conventional high voltage automobile ignition coil which is used to produce an electric spark that closes the circuit by the ionized passage it creates. This causes a condenser, charged up to 900-1200 V, to shorten, forming a high temperature plasma. Stored energies of up to 10J can easily be employed, but typically only 1 or 2 J are required. The high temperature plasma is created so rapidly that the cavity is pressurized, causing a supersonic jet of plasma to be issued through the orifice and penetrate into the charge.

Considerable work has been done on the development of such systems for automobile applications. Numerous patents (16) exist, and actual development and testing of jet igniters in engines was reported by Asik et al. (17), Fitzgerald (18), Wyczalek et al. (19), and Dale et al. (20). Relevant studies of plasma jets and their ignition characteristics were carried out by Topham et al. (21), Bradley and Critchley (22), Weinberg et al. (23, 24) and Oppenheim et al. (25, 26).

The latter conducted their investigations using a constant volume bomb where the combustible mixture was initially at rest, under atmospheric pressure and room temperature. Under such conditions they observed that:

1. The plasma jet entered the combustion chamber in the form of a turbulent plume which was imbedded in a blast wave headed by a hemispherical shock front,

2. The gasdynamic effects of the blast wave were dissipated by the time combustion started, after a delay typically of an order of 1 msec, so that ignition took place in the turbulent zone of the plume.

3. The depths of penetration of the jet was solely a function of its initial velocity; it could be thus controlled by the amount of energy deposited in the cavity, as well as its size and that of the exit orifice.

4. In direct contrast to spark ignition that produces a laminar flame which later becomes turbulent, here combustion was initiated in the form of a turbulent flame which upon leaving the plume tended to acquire a laminar character; the normal burning speed was, as a consequence, initially quite high decreasing monotonically as the flame kernel expanded.

5. With provisions made to fill the cavity with different feedstock, the most effective for ignition were hydrocarbons, among which those initially in liquid state were particularly effective -- a phenomenon interpreted as due to the action of hydrogen atoms, of which there was an abundance in the plasma created from such feedstocks.

6. Plasma jets were shown to be capable of igniting gaseous mixtures below the normal flammability limit.

Experiments with single and multi-cylinder engines operating with lean charge (A/F $>$ 18) demonstrated that plasma jets were capable of extending the LML, combustion being more rapid in that both ignition delay as well as the duration of the combustion process were reduced. However, the HC and NO emissions were increased while the emission of CO was only slightly reduced. To demonstrate these effects specifically, typical results obtained recently with an AFTM-CFR engine, operated at CR of 6/1, 1000 RPM, MBT spark timing, using unleaded fuel, are displayed in Figs. 5 and 6. The data has been obtained under identical conditions using a standard spark plug and a plasma jet igniter consuming 2J per pulse. The first two figures refer to WOT operation, while the other present the part throttle (PT) data.

The ignition delay and the duration of the combustion process were determined using the log PV^{γ} technique [27]. The end points on the graphs correspond to LML. The ability of the plasma jet to extend this limit is evident. Moreover, at A/F greater than 18, the power output and specific fuel consumption obtained with their use are definitely superior to those of a standard spark plug. While in both the WOT and PT operation combustion starts at about the same time, it ends definitely earlier with the use of the plasma jet than with the standard spark plug -- an effect which is exhibited particularly well in the case of PT operation, resulting in a clearly delineated increase in engine power output. Whether similar improvements could be obtained with EGR used in sufficient quantity for NOx control is yet to be established.

When plasma jets are used in automobiles, the extra electrical energy required, typically 1J vs. 50 mJ per pulse for a standard spark plug, must be produced on board at a relatively high cost in power. Asik et al. [17] examined this problem in a systematic test program and found that the fuel economy of a vehicle, measured by constant volume sampling (CVS-H) and steady state roll tests, was not significantly affected. Nonetheless, this should be still considered as a controversial matter. For example, Wyczalek et al. [19] reported that with the use of a plasma jet ignition system they have found no improvement in performance, or even its deterioration. Although they observed a reduction in an NOx emissions, they did not succeed in extending the LML and obtained actually higher HC emissions and lower power output. The reason for such poor performance can be most probably ascribed to geometric features of their plasma generator. Instead of using a cavity of a small volume and orifice diameter, as depicted in Fig. 4, the total volume of their cavity was 2.8 cm^3 (0.17 in^3) while, instead of an orifice, they used a nozzle with a throat diameter of 3.6 mm (0.14 in.).

PHOTOCHEMICAL, LASER, AND MICROWAVE IGNITION CONCEPTS

As pointed out in the Introduction, these concepts are only of interest to research and development of practical ignition systems rather than being themselves of any practical significance for actual engine application.

Photochemical techniques are based on the phenomenon of photolysis studied by Norrish [28], a method of established significance to chemical kinetic studies of oxidation reactions. Their use in practical systems has been examined quite thoroughly by Cerkanowicz [29, 30], leading to the development of a photochemical igniter described in Fig. 7. Since the igniter is effective only with windows transmitting vacuum ultra violet radiation, it was concluded that ignition is, in effect, caused by the action of oxygen atoms which are created by the dissociation of oxygen molecules caused by radiation below 245 nm, absorption at 180 nm being most efficient in this respect. It was found specifically that for ignition of a hydrocarbon/air mixture the critical concentration of oxygen atoms is of an order of 10^{14} atoms/cm^3. It was established, moreover, that the energy requirement to initiate combustion is essentially independent of the A/F of the mixture. The most interesting feature of this ignition system is that it is evidently capable of initiating combustion under similar conditions as the plasma jet with about the same expenditure in energy, although the plasma is in this case physically separated from the mixture by the window, guaranteeing that, unlike in the case of plasma jet, its effect is solely chemically kinetic in nature.

Lasers provide a non-intrusive generator of an ignition source whose energy, power, and location can be varied without any interference with the enclosure containing the combustible mixture. The laser beam is, for this purpose, focussed at a small point within the mixture to achieve breakdown, generating thereby a plasma kernel that acts as the ignition source. Hydrocarbon air mixtures have been thus successfully ignited under a variety of conditions by laser light in the visible and infrared regions of the spectrum. Such devices have been successfully used in combustion bomb tests to establish ignition limits for hydrocarbon/air mixtures [31], minimum ignition energy studies [32], as well as in single cylinder engines to establish such parameters as optimum timing and optimum location of the ignition source [33,34].

The investigations, carried out using an ASTM-CFR engine [33], demonstrated that, in comparison with a conventional spark ignition system, plasma bursts produced by a CO_2 laser near the center of the combustion chamber caused a more rapid pressure rise in the cylinder when the engine was operated at a compression ratio of 6:1, Fig. 8, leading to a significant extension of LML with as much as 16% EGR, Fig. 9. Besides the significant reduction in the specific fuel consumption, indicated in Fig. 9, the power output of the engine was increased and the HC and CO emissions were diminished, while NOx level was actually increased. The engine used by Dale et al. [33] had very little swirl, but that of Smith [34] was highly swirled. The latter did not find much difference in the rate of pressure rise, but observed shorter combustion duration when the laser spark was at the center of the compressed charge.

The effect of microwaves in treating the mixture at the flame front was studied theoretically by Ward and Tu [35], with particular concern towards the application of these means to an I.C. engine. The results they obtained indicate that efficient heating should be possible and that one should therefore expect an increase in the flame front velocity, producing high rates of burn and pressure rise. The conclusions of Ward and Tu have been corroborated by flame experiments conducted by Jaggers and Von Engel [36] and Tewari and Wilson [37], using an electric field at a frequency of 6MHz.

TORCH CELLS

Following the classical devices of air or energy cells in diesel engines, the use of pre-chamber cavities where the combustion is first initiated has been exploited in a number of engine designs [38-42]. Upon compression, these cavities are filled by the fresh charge where it is ignited, producing a turbulent torch that, in turn, promoted combustion in the cylinder. Examples of such systems are depicted in Figs. 10, 11, and 12, showing devices incorporated in a commercial car engine of Toyota, and in prototypes of Ford and Volkswagen respectively. The extension of LML obtained by their use were typically an order of 10 to 15% in A/F mass ratios while the effects on the emissions of HC, CO, and NOx, were either increased, decreased or remained unchanged, depending on the particular operating conditions at which the engines were tested.

In a recently reported study which was performed at the Institute of Engineering Thermophysics in Beijing, China, Wang et al. [43], the effect of a small torch cell on the performance of a rotary engine was examined, demonstrating a definite extension in the lean limit with concomitant improvements in power output and specific fuel consumption, starting at an equivalence ratio of 1.05 and extending down to a little below 0.95.

An extreme case of a torch cell has been patented by May in 1977 [44,45,46] and referred to as the Fireball engine, Fig. 13. Here practically all the charge is squashed into a cell immediately below the exhaust valve, with a swirl produced by channel guides on the top of the piston and in the cylinder head. With the spark gap located at the side of the cavity, the May engine was capable of operating at an A/F ratio of 22:1 and compression ratio of 15:1. Tests performed by Ricardo & Co. Engineers, Ltd. in England and The Associated Octel Company Ltd. in France [45] demonstrated a definite decrease in the emissions of HC associated, however, with a significant increase in NOx [46].

One should note that the combustion chamber of the PROCO engine portrayed here in Fig. 2 incorporates the principle of torch cell in an extreme case, similar to that of May, but with the cavity in the piston head. In our opinion the fundamental drawback in these two cases is associated with a significant expansion around the relatively sharp corners at the exit of the cavity. This occurs when the volume of the compressed charge is increased due to piston motion beyond the TDC, producing optimum conditions for the detrimental effects of bulk quenching. It is of interest to observe that it is essentially the same type of turbulent flow generated at the efflux from the cavity that in the case of small torch cells enhances ignition of the fresh charge in the main chamber while, in the case of large cells which accommodate virtually the whole charge, causes extinction of the flame. Phenomena of this kind are, as it will be described here later, intimately associated with the process of extinction of combustion and its re-establishment after a certain time lag when a turbulent jet flows from a reservoir into a fresh charge in the combustion chamber.

DIVIDED CHAMBER STRATIFIED CHARGE ENGINE SYSTEMS

These systems can be considered as torch cells provided with means for enriching the mixture to obtain an effective stratification of the charge. This is produced either by feeding a richer mixture to the pre-chamber through a third valve (the basic principle of the so-called three-valve engines) or by using a fuel injector mounted directly to the pre-chamber. The two systems are illustrated by the otherwise identical design of Volkswagen, Fig. 14.

The concept of a three-valve stratified charge engine dates back to 1918 when Ricardo first patented such a system. In this patent the third valve at the intake to the pre-chamber was just kept closed by a helical spring, so that it was opened by the suction at the intake stroke, filling the cavity with a pre-carbureted rich mixture, while the piston could suck in at the same time a leaner charge through the inlet valve. Turkish [47] gave a comprehensive review of such designs, their operating characteristics in comparison with conventional engines, as well as results of a computer simulation analysis of the performance of a stratified charge engine.

The proceedings of a recent I. Mech. E. Conference on Stratified Charge Engines [48] contains several papers on engine characteristics and related research. Moreover, test results of such engines were reported by Wyczalek et al. [49], Date, et al. [50], Yagi et al. [51].

The number of variables that have to be optimized for these engines is, of course, far greater than in the standard case. Nonetheless, experimental and production engines show that, by proper combination of the rich mixture for torch ignition of the lean charge, fuel economy can be definitely improved, while CO and NOx emissions can be significantly reduced. However, due to the enlarged thickness of the quench layer at higher A/F ratios, the HC emissions are usually quite large and the engine power is relatively low, requiring larger displacements to produce the same performance as the homogeneous S.I. engines.

Of all the engines of this kind it is perhaps the Honda CVCC [50,51] that has been the most successful, Fig. 15. Here, with the overall A/F ratio of about 20, the flame is allowed to propagate through the lean charge at a relatively slow normal burning velocity, commensurate with this mixture strength. The slow rate of burning enhances the oxidation of HC and CO in the exhaust gases containing a relatively large amount of excess air. At the same time the maximum temperature is significantly reduced, inhibiting decisively the formation of NOx. It is for this reason that, as it is well known, the Honda CVCC can still comply with the California pollution standards without a catalytic converter.

FLAME JET IGNITERS

These systems represent an extreme case of the divided stratified chamber concept that is attained when the diameter of the orifice at the exit from the pre-chamber is significantly reduced. One obtains then a flame jet that can penetrate deeply into the main charge. In fact, in order to avoid quenching at the walls, the penetration depth has to be restricted by using relatively small pre-chamber volumes. Interestingly enough, such systems have been developed principally in the Soviet Union [52-56].

Under these conditions, in contrast to the essentially uninterrupted propagation of the torch, as it issues from the pre-chamber and spreads out throughout the main charge, the jet comes out of the orifice at a relatively high velocity, and the ensuing turbulence it creates shears the flame apart so that it is, in effect, temporarily extinguished. As a consequence, a large number of small size turbulent kernels of flamelets, or active particles, are seeded throughout the charge. After a short induction period, rapid combustion of the lean mixture in the combustion chamber is thus initiated at a large number of distributed ignition sites.

The most advanced studies of this system have been carried out by Gussak et al. [55,56]. Engines developed in this connection were of the three-valve, divided chamber, stratified charge type, with ignition taking place in a small fuel-rich pre-chamber (volume: 2-3% of clearance volume, equivalence ratio: 1.4 to 2.5) furnished with one or more sharp edge orifices (section area: 3-5 mm^2 per 1 cm^3 of pre-chamber volume) to produce the flame jets, Fig. 16. The over-pressure built up in the pre-chamber is carefully maintained at a sub-critical level, so that the jet is essentially subsonic in order to prolong as much as possible the process of partial oxidation of the rich mixture where the combustion was started, as it is ejected into the main charge containing a relatively large amount of excess air (equivalence ratio of an order of 0.5).

The process of ignition caused by flame jets was studied quite extensively, using combustion bombs and engines, as well as experimental steady flow systems. As far as engine performance is concerned, the advantages claimed by Gussak et al. for this type of ignition are: an extension of the LML up to A/F of 33/1, definite improvement in fuel economy and significant decrease in fuel octane requirement, associated with lower exhaust emissions than those of comparable homogeneous, as well as stratified charge engines operated at the same conditions.

The results were interpreted on the basis of chemical kinetic chain branching theory of Semenov [57], according to which the ignition is due in principle to the action of methyl radical and hydrogen atom in enhancing the chain branching mechanism. Interestingly enough, Wang et al. [43], who referred to the papers of Gussak and Semenov, rationalized their experimental data on the basis of a purely thermal theory. Evidently the process of ignition by a flame torch or a flame jet warrants further study, even at steady flow conditions, let alone pulse operation required for I.C. engines.

COMBUSTION JET IGNITION CONCEPTS

When the orifice diameter is sufficiently small to allow the pressure in the pre-chamber to be built up beyond the critical level, a supersonic jet of combustion products is obtained. As demonstrated by Oppenheim et al. [25], the ignition process in an extra lean mixture is in this case essentially the same as that initiated by a plasma jet. Under similar conditions there is an induction period of about the same duration (approximately 1 msec) after which combustion starts at a number of sites within the turbulent plume created by the supersonic jet.

Engines outfitted with such an ignition system have been operated successfully by O'Neill [58], and currently a fundamental study of this process, using a combustion bomb, is underway at the University of California [25,26]. Salient features of the igniter used for this purpose are displayed in Fig. 17. In order to control the timing of the jet, the orifice is furnished with a conical valve operated by a solenoid counter-spring system. The valve rod acts at the same time as the high voltage electrode. With the valve closed, the pre-chamber is filled with combustible mixture and ignited by a spark between the central rod and an electrode extending from the side wall close to the orifice plate. By adjusting the orifice diameter between 1 and 3 mm and varying the mixture ratio, both subsonic and supersonic jets can be obtained. The relative merits of the two are currently under study.

EGR IGNITION SYSTEM

Another extreme case of a stratified charge concept, on the opposite side of the spectrum of all the possibilities than those described above, is a system using a sufficiently large amount of exhaust gases to ignite their mixture with the fresh charge. Such a system has been developed, up to commercial application, by Onishi et al [59] in a two-stroke engine mode, Fig. 18. The exhaust gases are stored in the crankcase and admitted to the cylinder through a port situated, in close vicinity of the inlet port, just above the piston head at BDC. In the course of compression, the exhaust gases are mixed uniformly in the right proportion with the fresh charge, causing auto-ignition when the temperature of the mixture attains a sufficiently high value near the TDC. Since the exhaust gases are by then quite homogeneously distributed throughout the fresh charge, combustion is initiated all over the combustion mixture, while, as a consequence of significant dilution, the combustion process is sufficiently slow to avoid the formation of blast waves. Instead of a flame propagating through the charge, one thus has an essentially homogeneously distributed combustion process consuming the charge at the proper rate throughout its bulk. The authors refer to this process as the Active Thermo-Atmosphere Combustion.

The engine is started with a conventional spark plug, while the EGR system is turned off. After a sufficient amount of EGR is admitted the spark plug is, in turn, switched off. Surprisingly enough the operation of the engine is then significantly smoother, the cycle-to-cycle variation in peak pressures becoming practically annihilated. At the same time remarkable improvements are obtained in specific fuel consumption, as well as in exhaust emissions.

In commercial application, single cylinder engines of this type, with a displacement of about 100 cm^3 operate at a compression ratio of from 6.0 to 6.8 and a speed of 3600 RPM, driving electric generators, delivering from 0.8 to 1.25 kW of rated power.

Although there are no independent checks available of all the claims made by Onishi et al. [59], the engine system they developed should be recognized as a remarkable proof of the ultimate in enhanced ignition, whereby a virtually infinite number of ignition sources are distributed throughout the fresh charge to initiate combustion in bulk at a proper rate of burn, yielding at the same time clean and efficient operation of the engine.

CONCLUSIONS

Our review of enhanced ignition systems emphasizes the concept of staging the processes of initiation and propagation of combustion. In the case of electric systems, this principle is applied to the initial stages of ignition, in that the plasma yields a sufficient amount of active species or a sufficiently high temperature to promote the chain branching reactions to proceed at a sufficiently high rate to maintain and propagate the flame. In the case of chemical ignition systems, the propagation of the combustion process is staged, in that part of it is conducted in a pre-chamber to generate in effect ignition sources that are subsequently used to initiate combustion in the main chamber.

Thus, in order to establish a relative position of various ignition systems they can be lined up on the scale of relative energies, ϵ , the ratio of energy consumed by the ignition system, or contained in the pre-chamber, to that of the compressed charge in the main chamber. It should be noted that such a scale is certainly not commensurate with relative merit. Since most of the enhanced ignition systems are based on the use of a pre-chamber, one has also a scale of relative volumes, ν, the ratio of the volume of the pre-chamber to that of the compressed charge. Thus, for the sake of comparison of their kind, but certainly not merit, the ignition systems can be located on the plane of relative volumes and energies as portrayed in Fig. 19.

The standard and high energy spark plugs are at the lowest level on the energy scale and zero relative volume. Plasma jets are one to two orders of magnitude higher in relative energy and at a finite value of relative volumes. Flame and combustion jets are another order of magnitude higher in relative energy, but since they use chemical rather than electrical power, the actual cost in energy expenditure is in their case much lower. The pre-chambers or divided chamber stratified charge engines are distributed over a relative energy band of from 10^{-2} to 10^{-1}, and various fractional values of relative volumes of up to 0.2, as displayed in Fig. 19. The May Fireball engine, considered here as the extreme case of the torch cell system, is estimated at a location corresponding to relative energies and volumes, both of an order of 10^2, while the EGR system of Onishi is on the other side of the scale with the relative volume of the same order of magnitude as the May engine, but with virtually negligible relative energy.

It is amusing to observe that the diesel engine systems can be located on the same plane at the relative energies of infinity, while the open chamber stratified charge engine can be located somewhere along the diagonal between $\epsilon = 0, \nu = 1$ and $\epsilon = \nu = 10^2$. Moreover, it is of interest to note that diesel engines combining fuel oil injection with carbureted alcohol/air charge, bring in effect the relative energy down to the level of one, bridging the gap between non-premixed and premixed charge engines. Perhaps it is in this area that the future of I.C. engines is situated.

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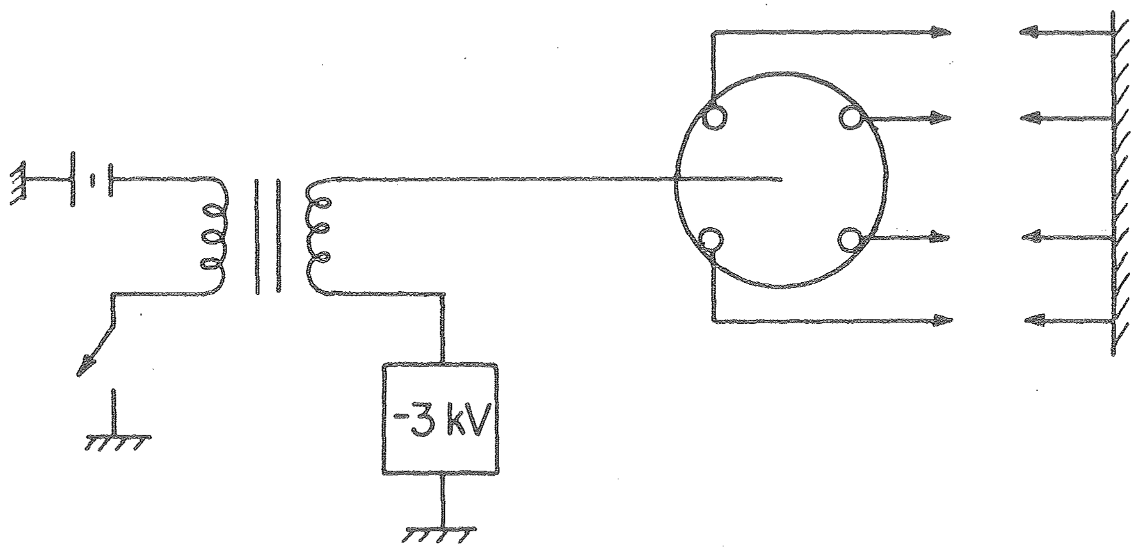


Figure 1A. Schematic of Supplementary Secondary Energy (SEE) ignition system (Ref. 12)

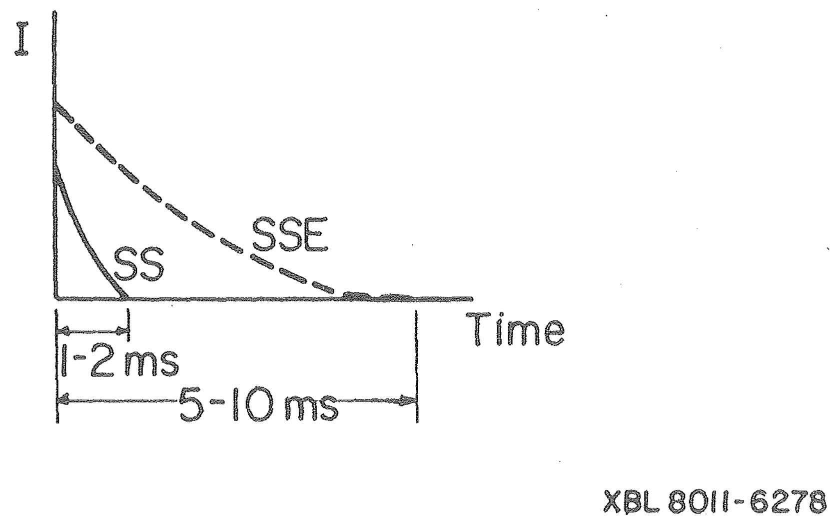
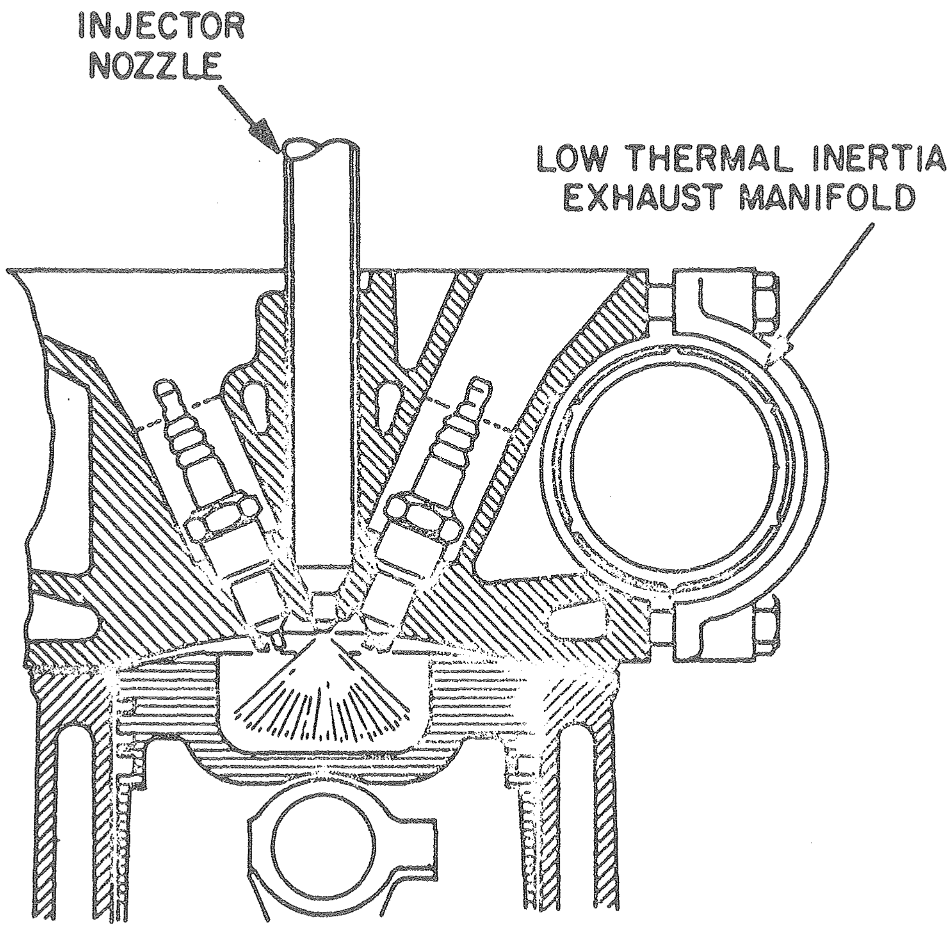


Figure 1B. Discharge characteristics of Supplementary Secondary Energy (SSE) and Standard Spark (SS) ignition systems (Ref. 12)



XBL 8011-12064

Figure 2. Combustion chamber of Ford PROCO engine (Ref. 60)

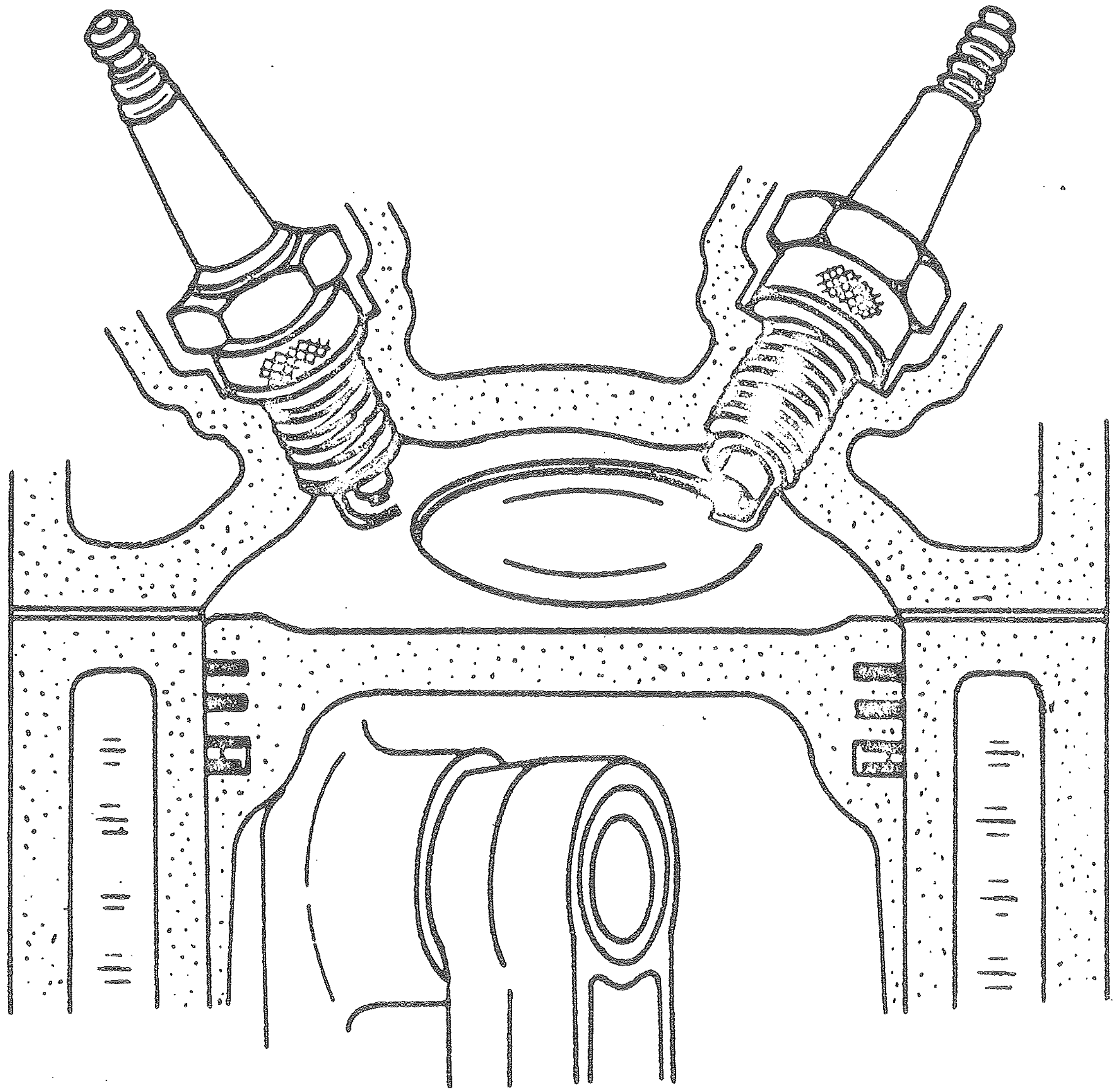


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Figure 3. Combustion chamber of Datsun engine (Ref. 61)

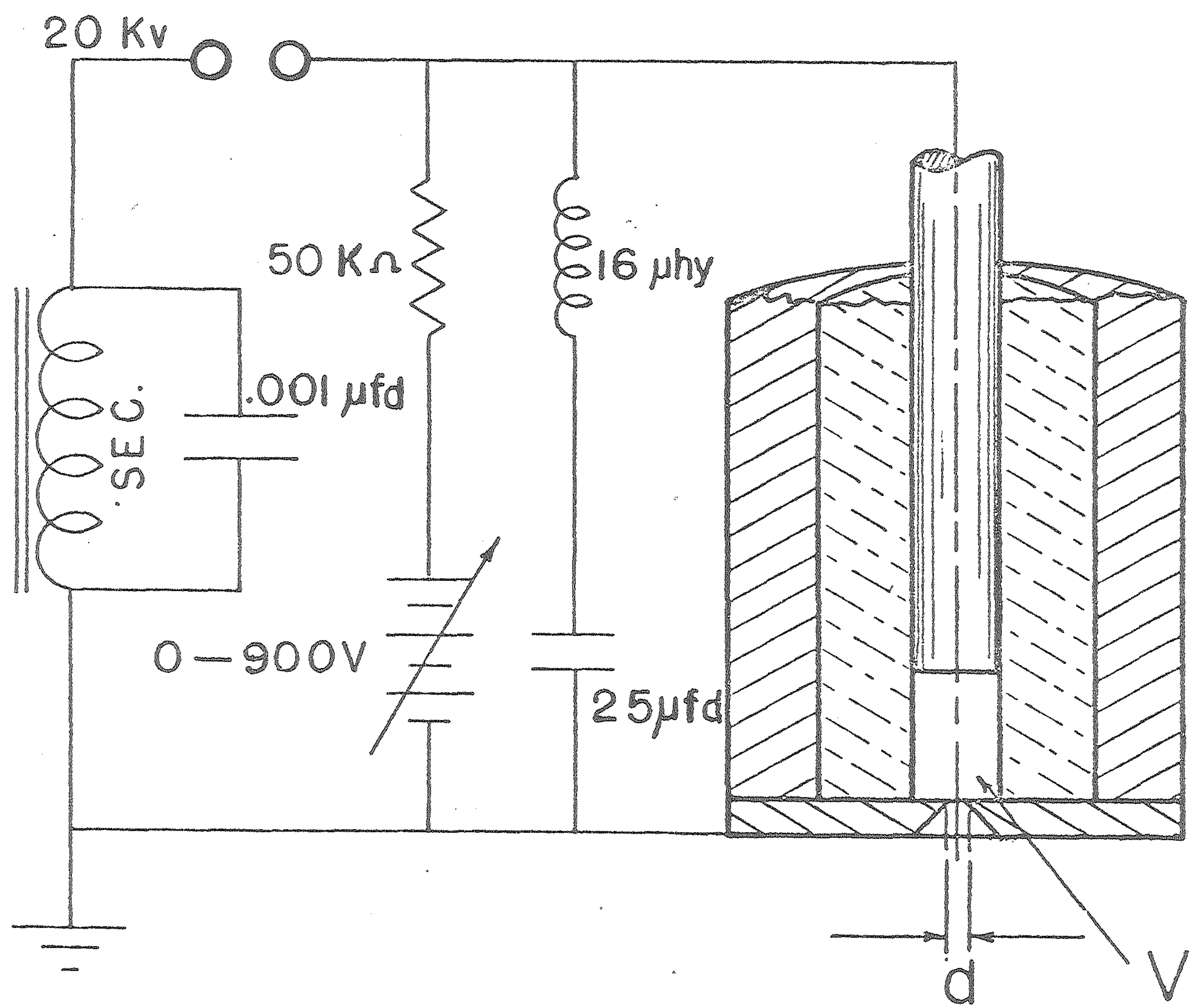

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Figure 4. Schematic of a plasma jet igniter, $d \simeq 1$ mm, $V \simeq 10$ mm^3

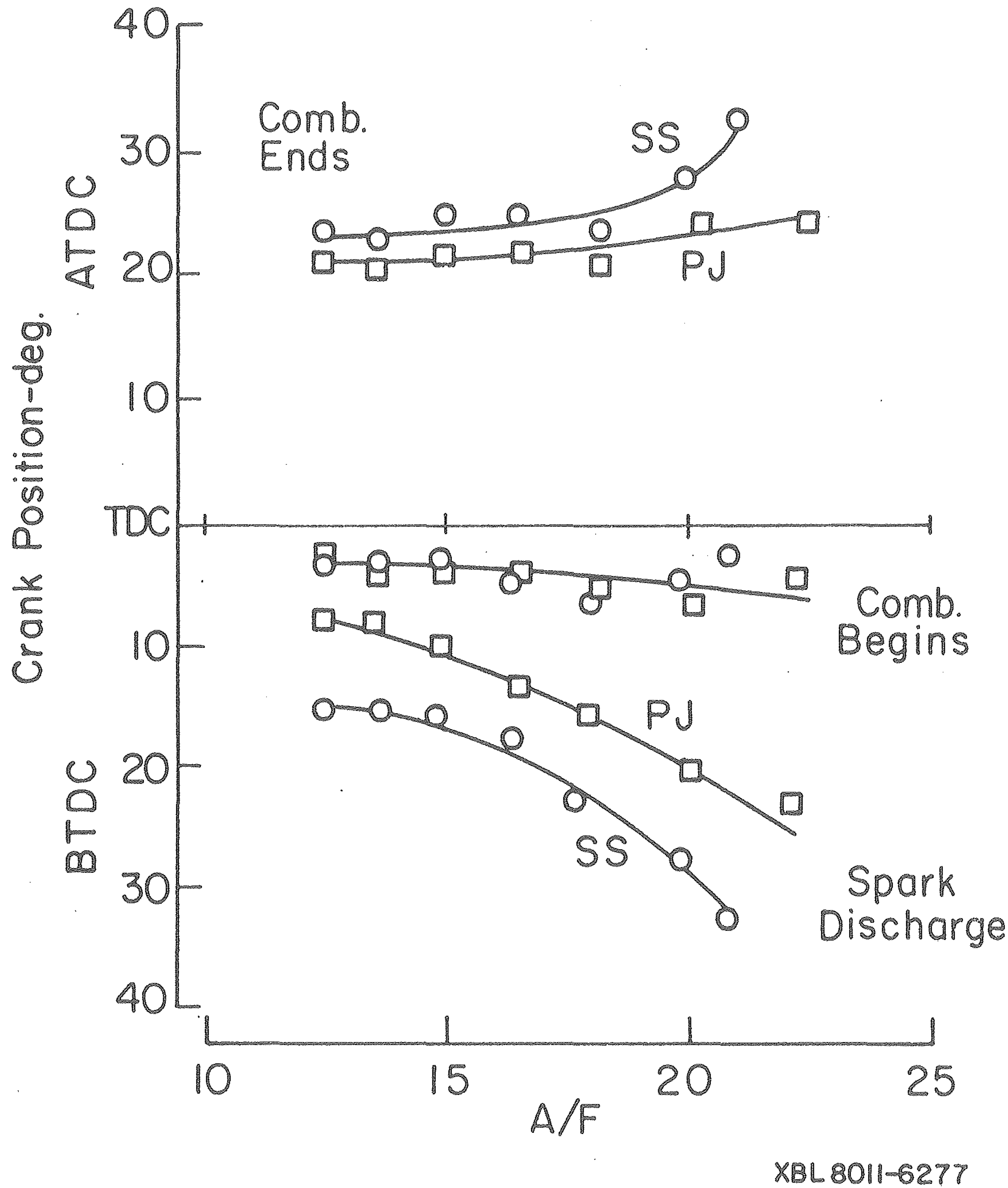

Figure 5A. Measured engine combustion characteristics with Standard Spark (SS) and Plasma Jet (PJ) ignition systems. ASTM-CFR engine, 1000 RPM, 6:1 CR, MBT, unleaded gasoline, WOT, air flow 15.9 Kg/HR

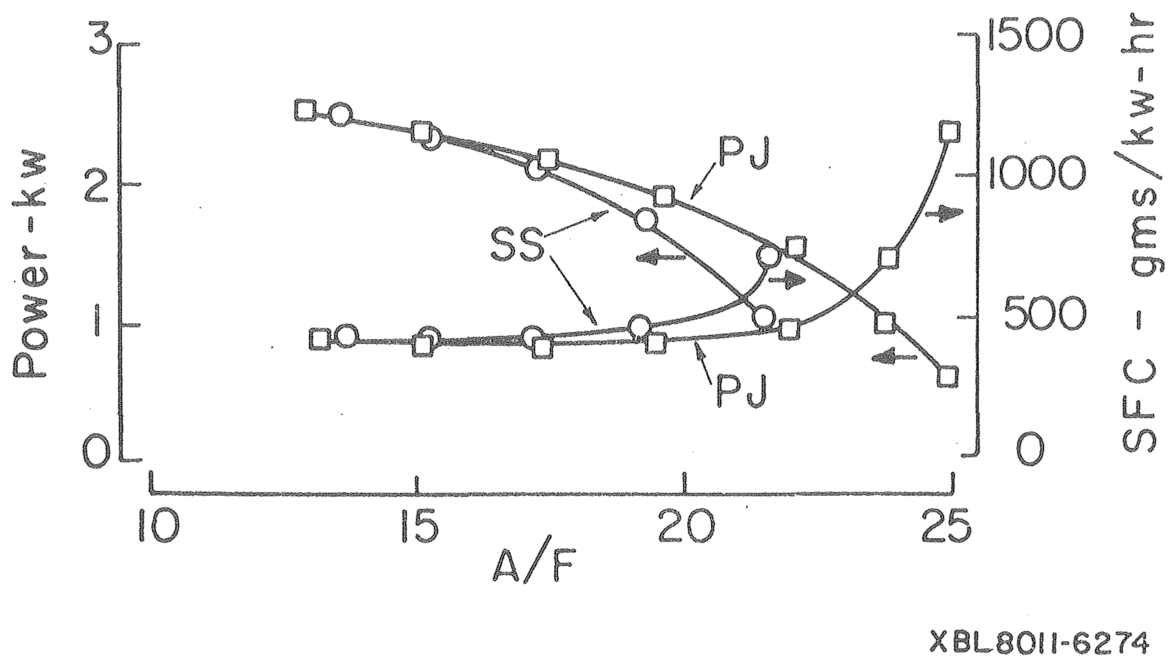

Figure 5B. Measured engine performance with Standard Spark (SS) and Plasma Jet (PJ) ignition systems. ASTM-CFR engine, 1000 RPM, 6:1 CR, MBT, unleaded gasoline, WOT, air flow 15.9 Kg/HR

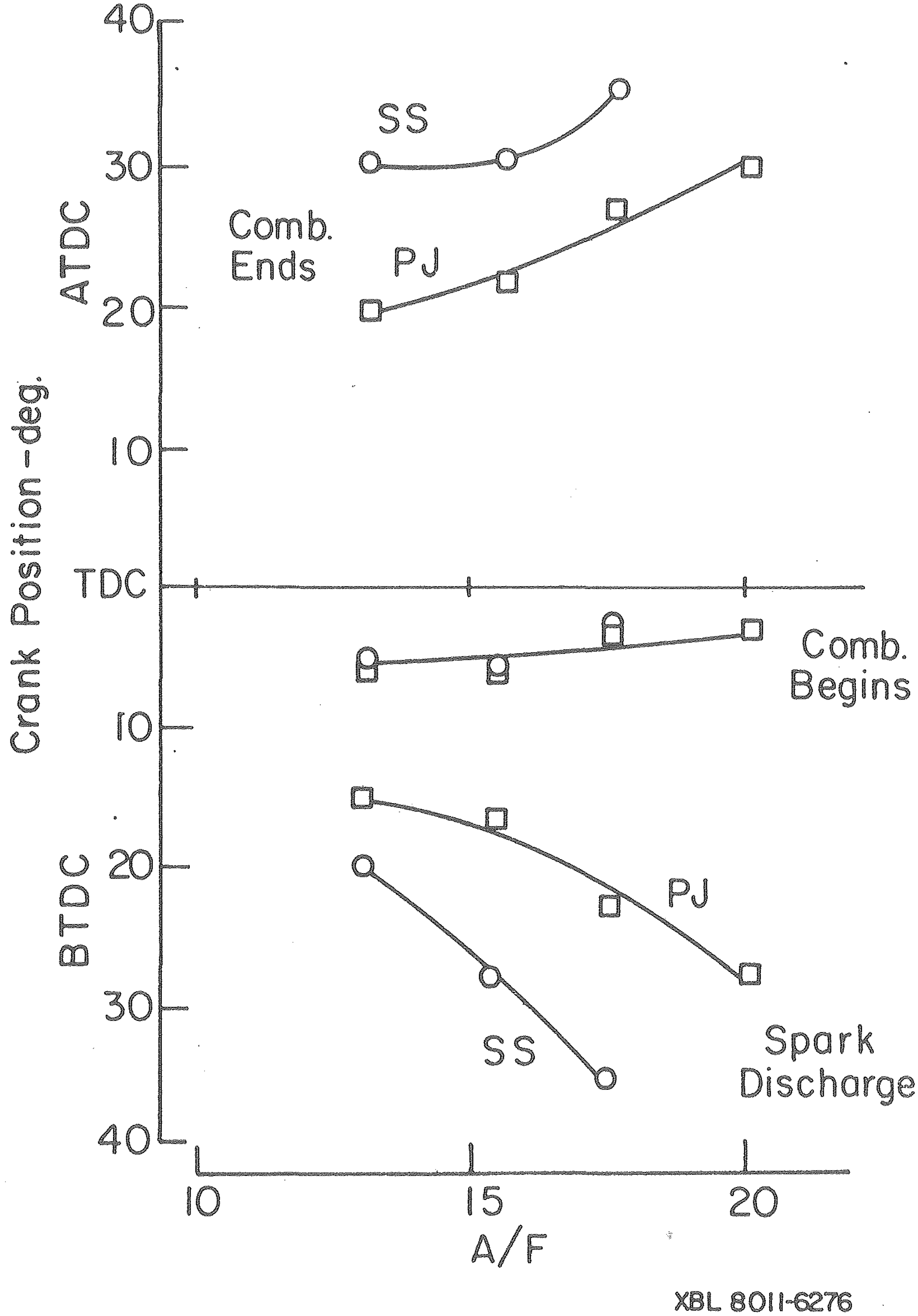

Figure 6A. Measured engine combustion characteristics with Standard Spark (SS) and Plasma Jet (PJ) ignition systems. ASTM-CFR engine, 1000 RPM, 6:1 CR, MBT, unleaded gasoline, air flow 8.6 Kg/HR

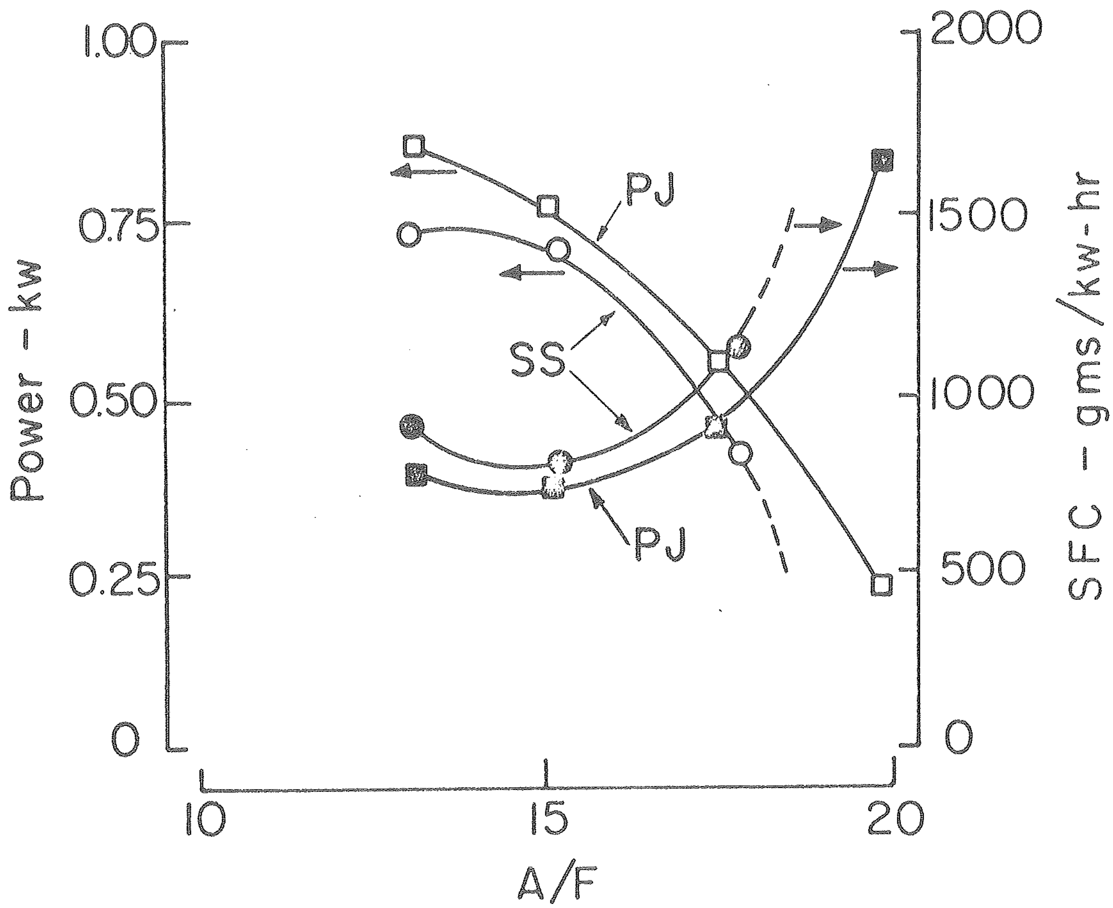

Figure 6B. Measured engine performance with Standard Spark (SS) and Plasma Jet (PJ) ignition systems. ASTM-CFR engine, 1000 RPM, 6:1 CR, MBT, unleaded gasoline, air flow 8.6 Kg/HR.

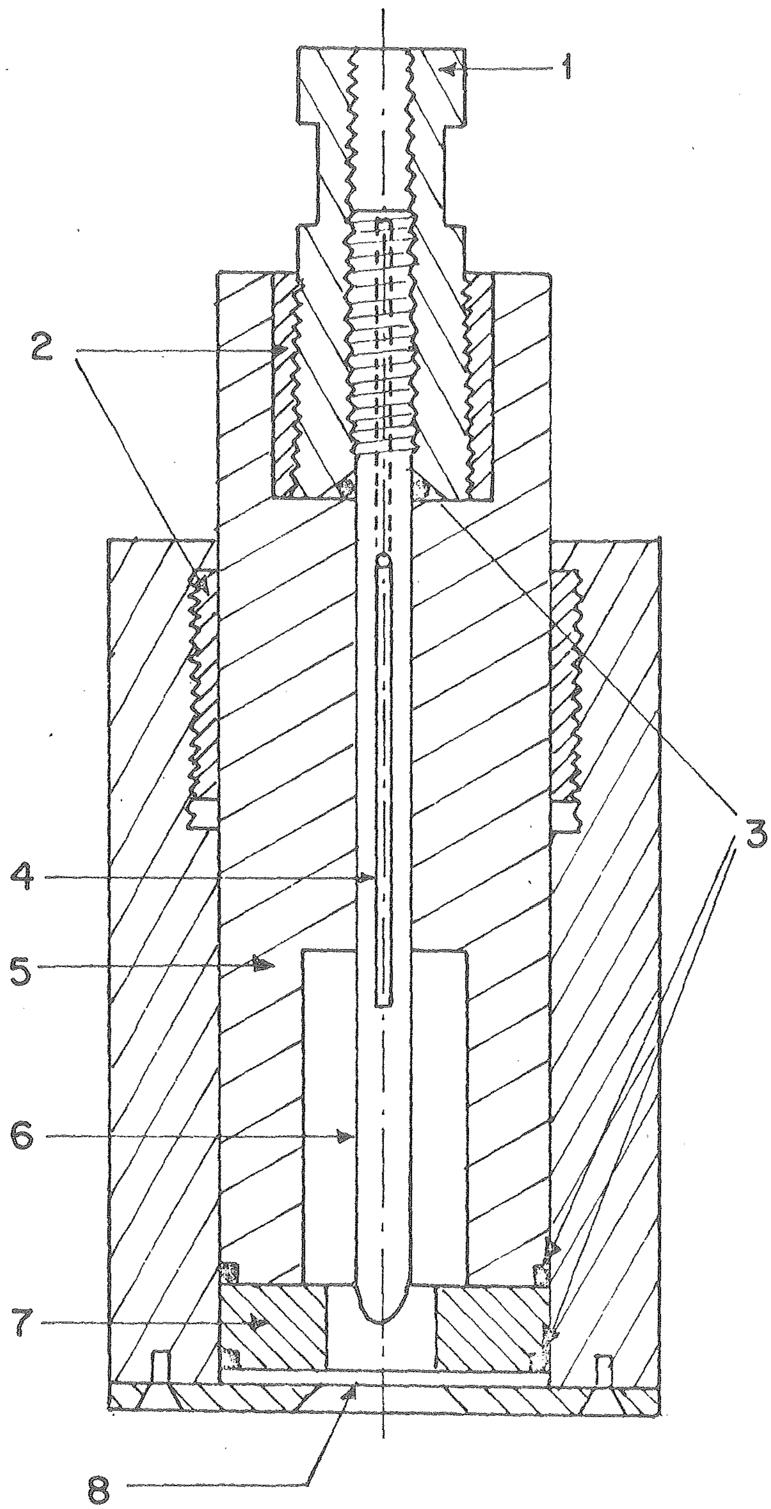

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Figure 7. Photochemical igniter; 1 - gas inlet port and high voltage lead, 2 - brass inserts, 3 - O rings, 4 - gas feed through, 5 - Macor insulator, 6 - stainless steel anode, 7 - stainless steel cathode, 8 - sapphire window.

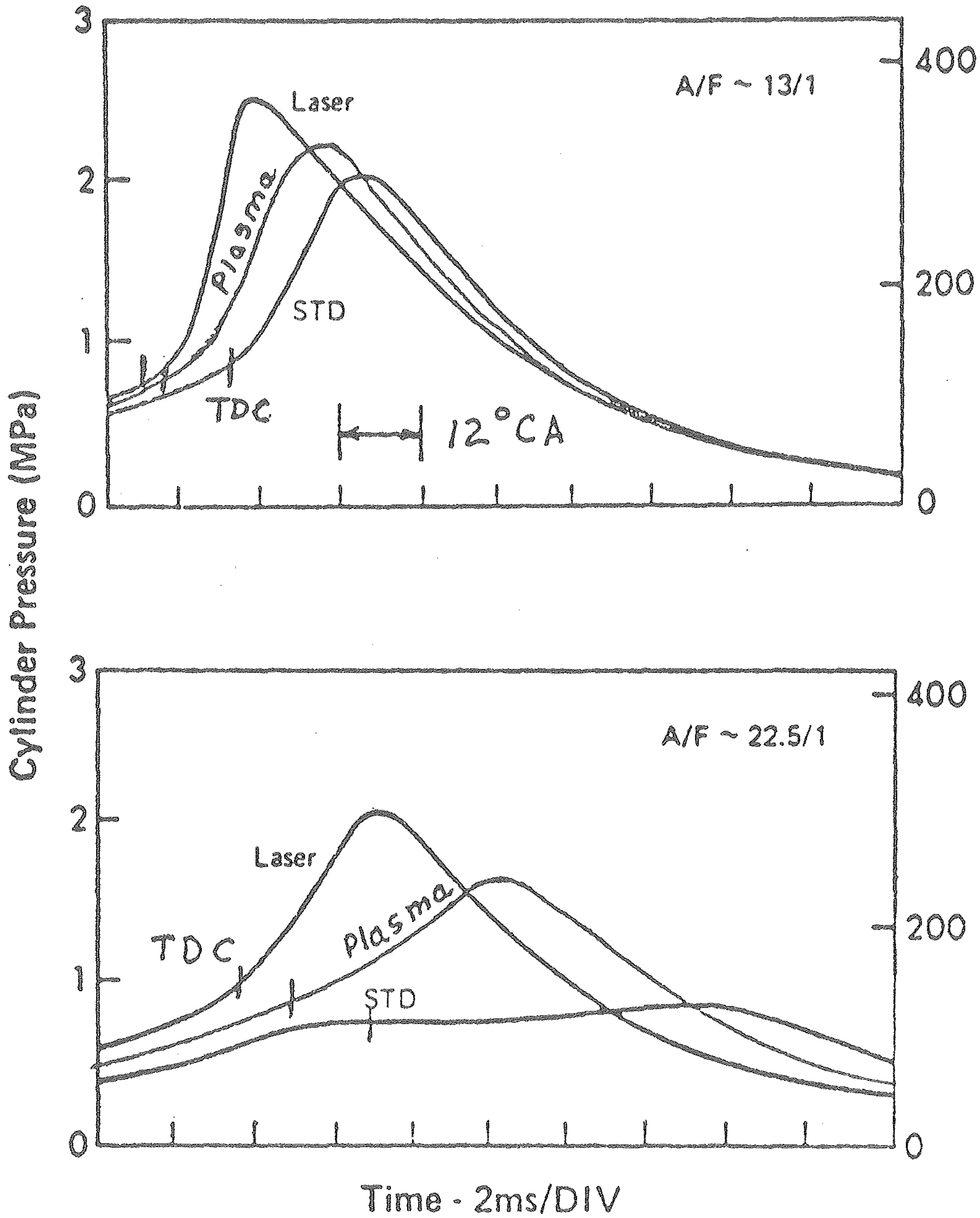

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Figure 8. Time averaged cylinder pressure traces for various ignition systems starting at the time of spark firing. Vertical marks are respective top dead center locations (Ref. 20, 33).

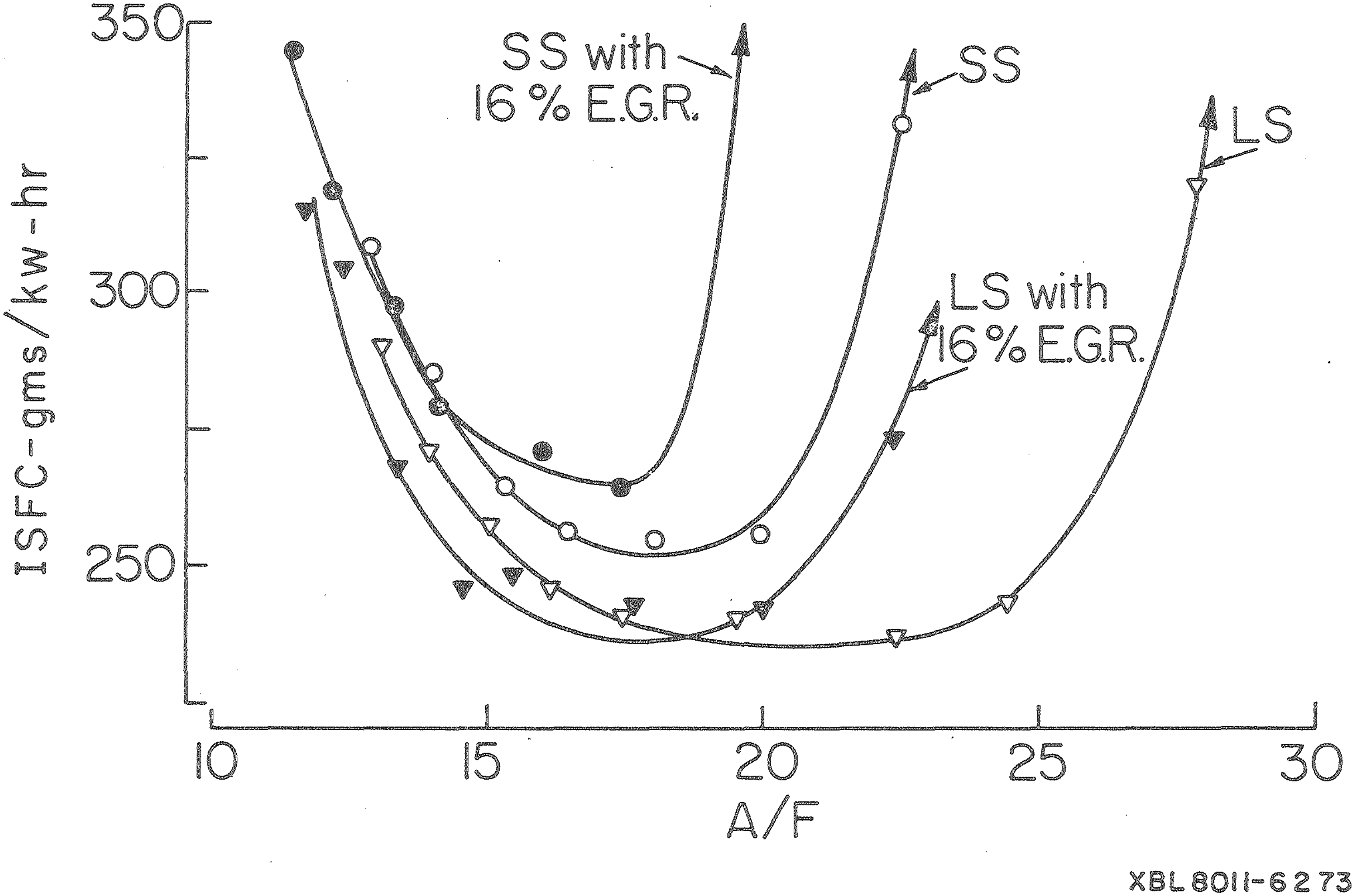

Figure 9. Engine specific fuel consumption with Standard Spark (SS) and Laser Spark (LS) ignition systems (Ref. 33).

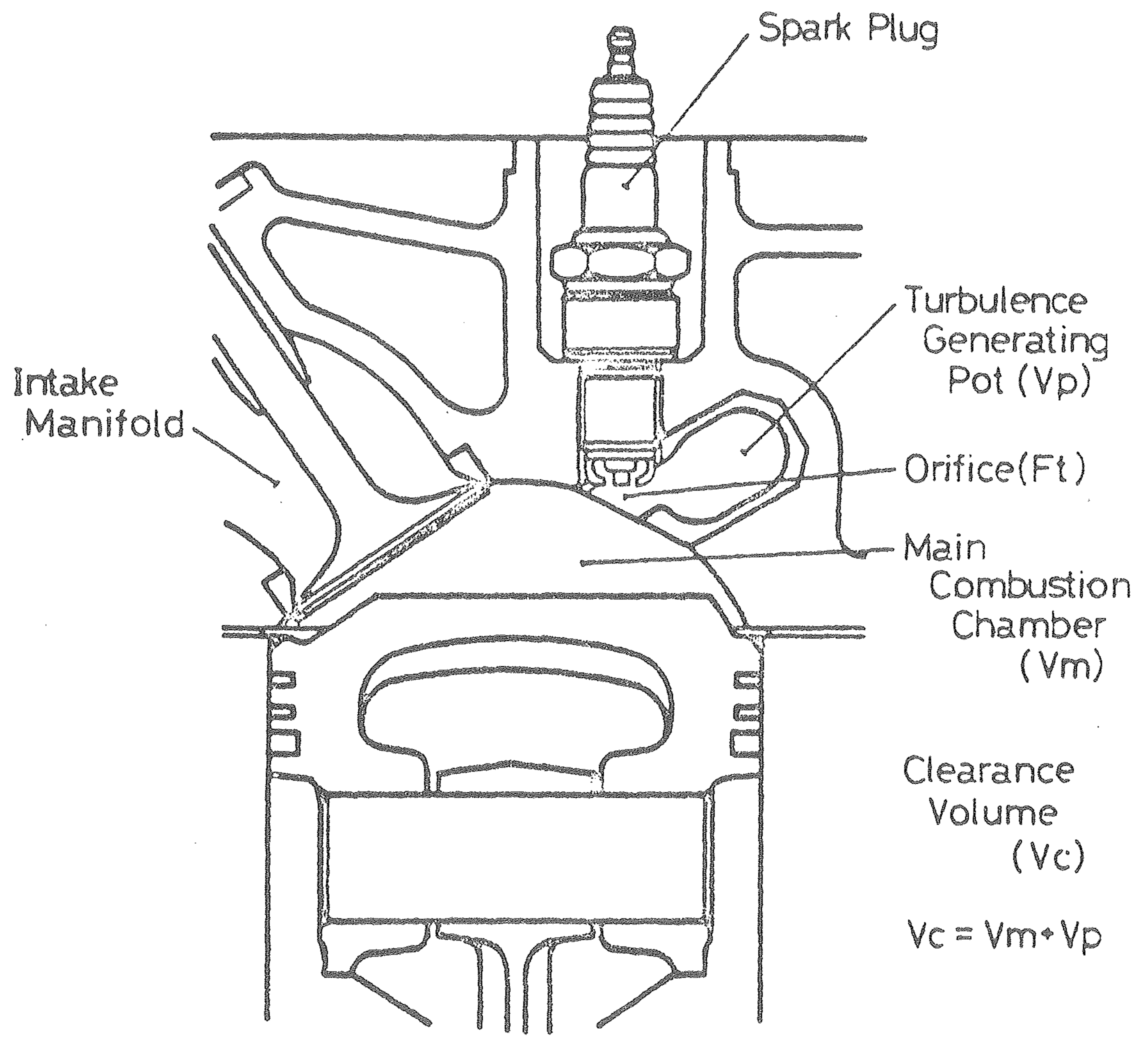

Figure 10. Torch chamber of Toyota (Ref. 38).

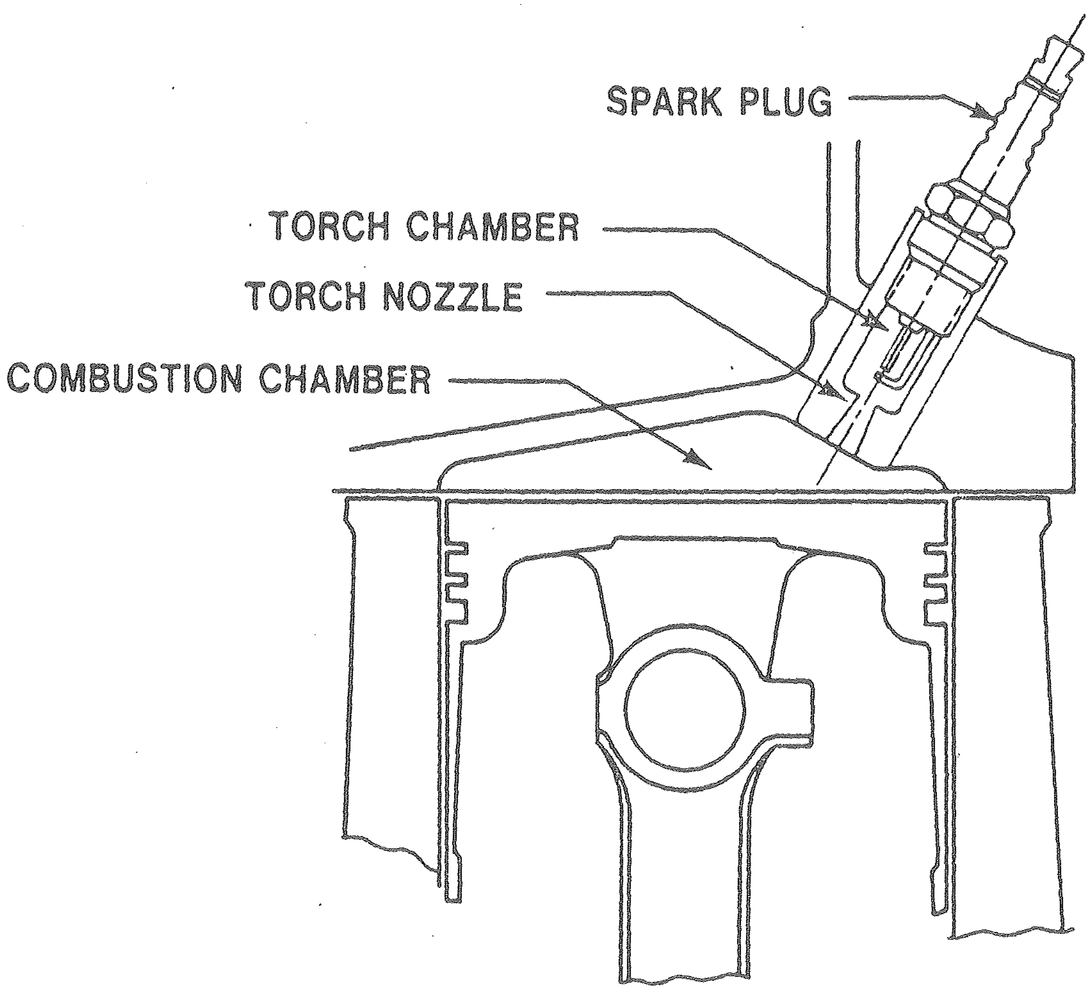

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Figure 11. Torch chamber of Ford (Ref. 39).

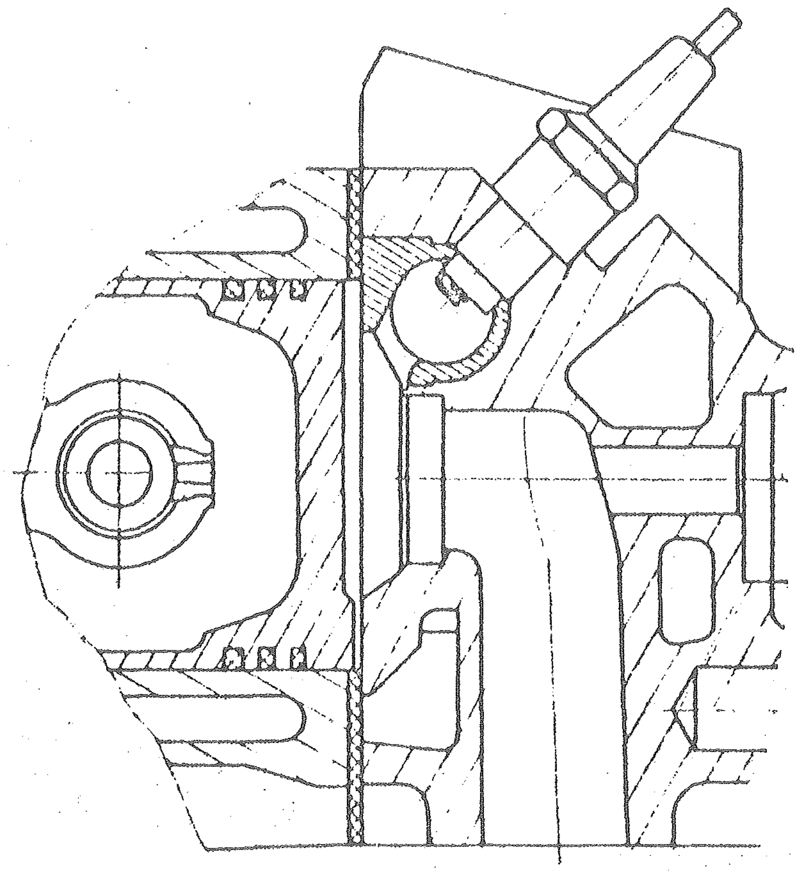

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Figure 12. Torch chamber of VW (Ref. 42)

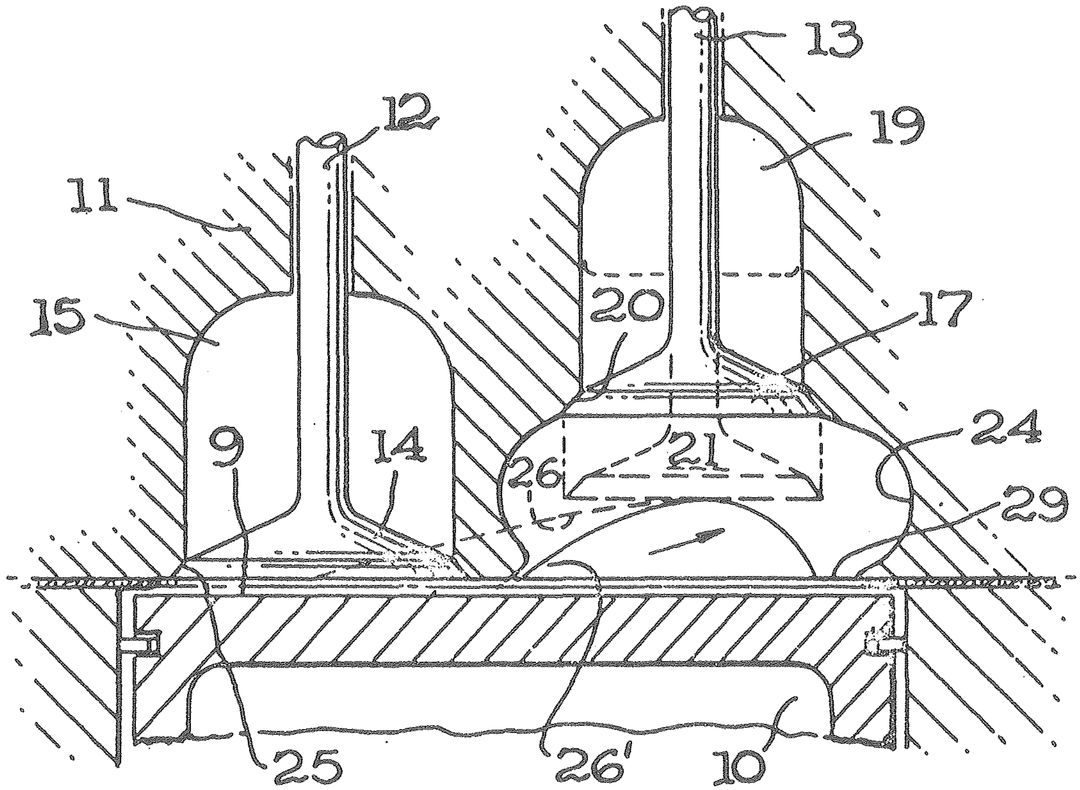

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Figure 13. Combustion chamber of May engine (Ref. 44); 9 - flat piston head, 10 - piston, 11 - cylinder head, 12 - intake valve, 13 - exhaust valve, 14 - valve disc, 15 - intake port, 17 - valve disc, 19 - exhaust port, 20 - outlet aperture, 21 - swirl chamber, 24 - circumferential wall, 25 - inlet aperture, 26 - cavity, 26' - guide channel, 29 - swirl chamber opening.

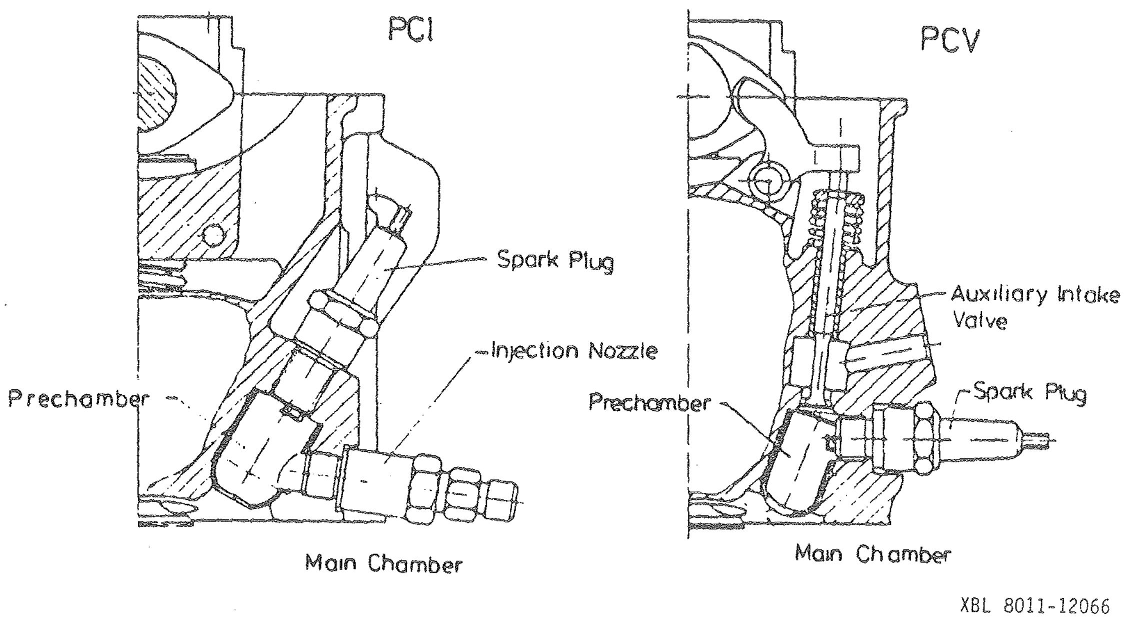


Figure 14. Combustion chambers of VW-PCI- and VW-PCV-combustion processes (Ref. 48).

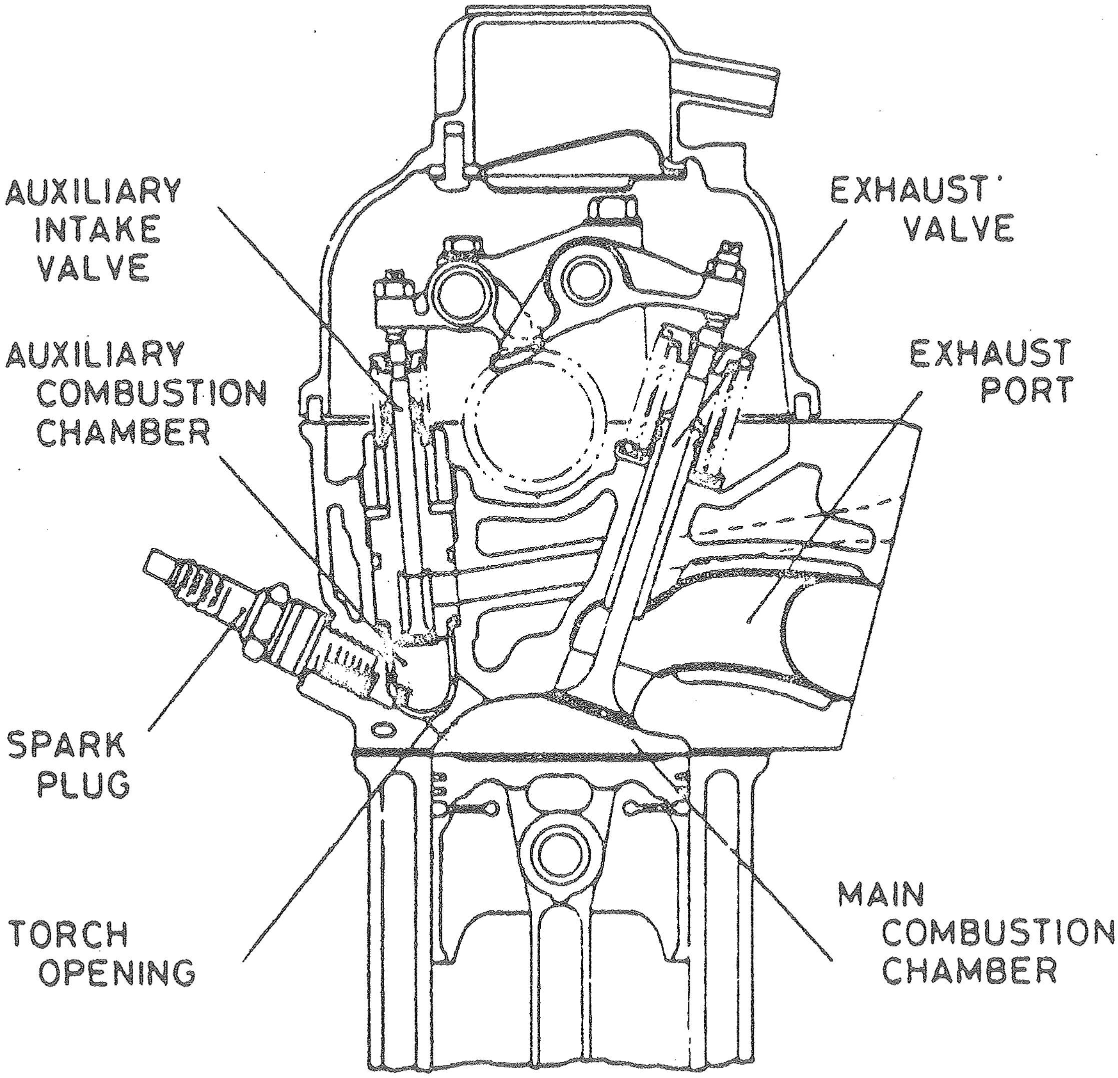
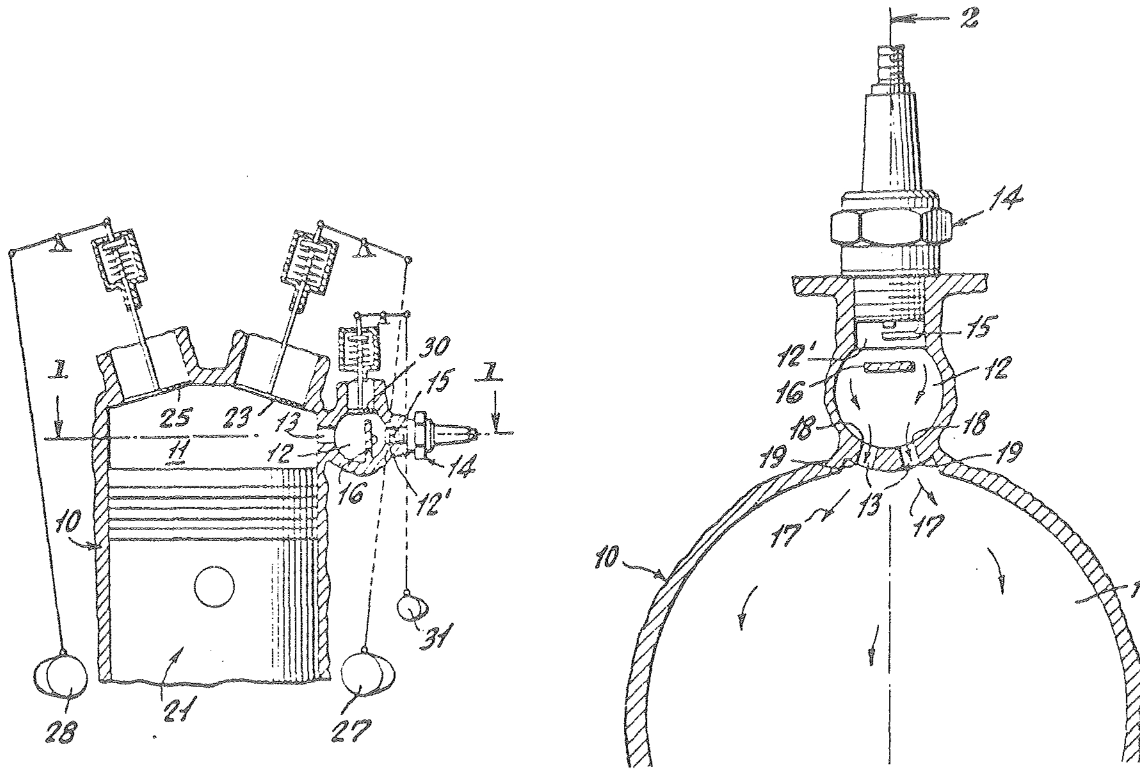


Figure 15. Combustion chamber of Honda CVCC engine (Ref. 50).



XBL 8011-12059

Figure 16. Method of pre-chamber torch ignition in internal combustion engines by L. A. Gussak (Ref. 54); 1 - section displayed on the right side, 2 - section displayed on the left side, 10 - cylinder, 11 - main combustion chamber, 12 - prechamber, 12' - recess section in pre-chamber, 13 - orifice for injection, 14 - conventional spark plug, 15 - spark plug electrodes, 16 - baffle separating pre-chamber recess section, 17 - direction of flame jet, 18 - smooth inlet to orifice, 19 - sharp outlet from orifice promoting turbulence, 21 - piston, 23 - intake valve, 25 - exhaust valve, 27 - cam for intake valve, 28 - cam for exhaust valve, 30 - intake valve for pre-chamber, 31 - cam for pre-chamber intake valve.

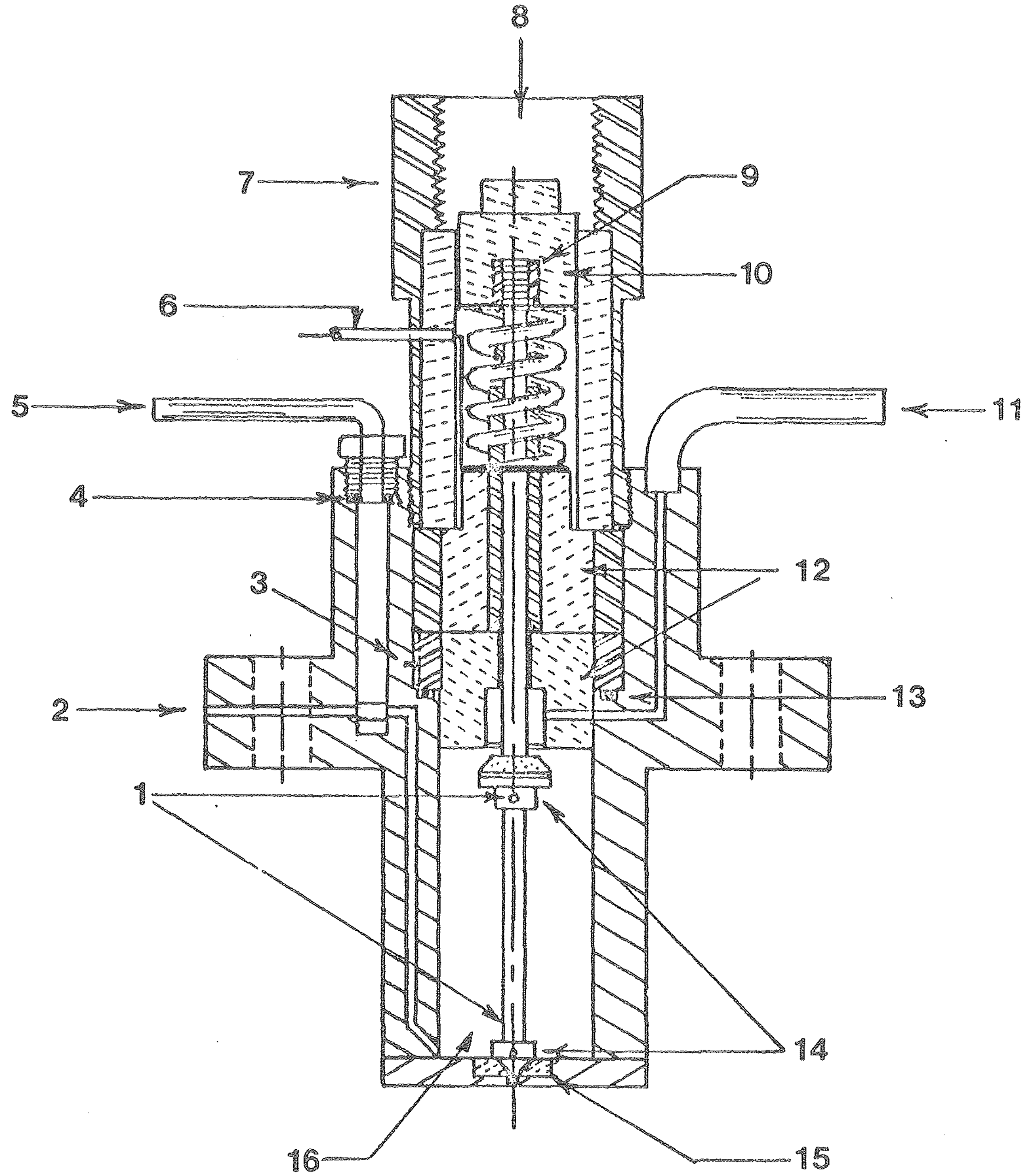


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Figure 17. Combustion jet igniter; 1 - valve rod, 2 - purge outlet, 3 - alignment slot and key, 4 - packing gland, 5 - shut off vlave, 6 - high voltage lead, 7 - solenoid support, 8 - solenoid plunger, 9 - rod supporting nut, 10 - Macor bonnet, 11 - gas inlet, 12 - Macor guides, 13 - O ring, 14 - valves, 15 - tapered orifice, 16 - combustion chamber.

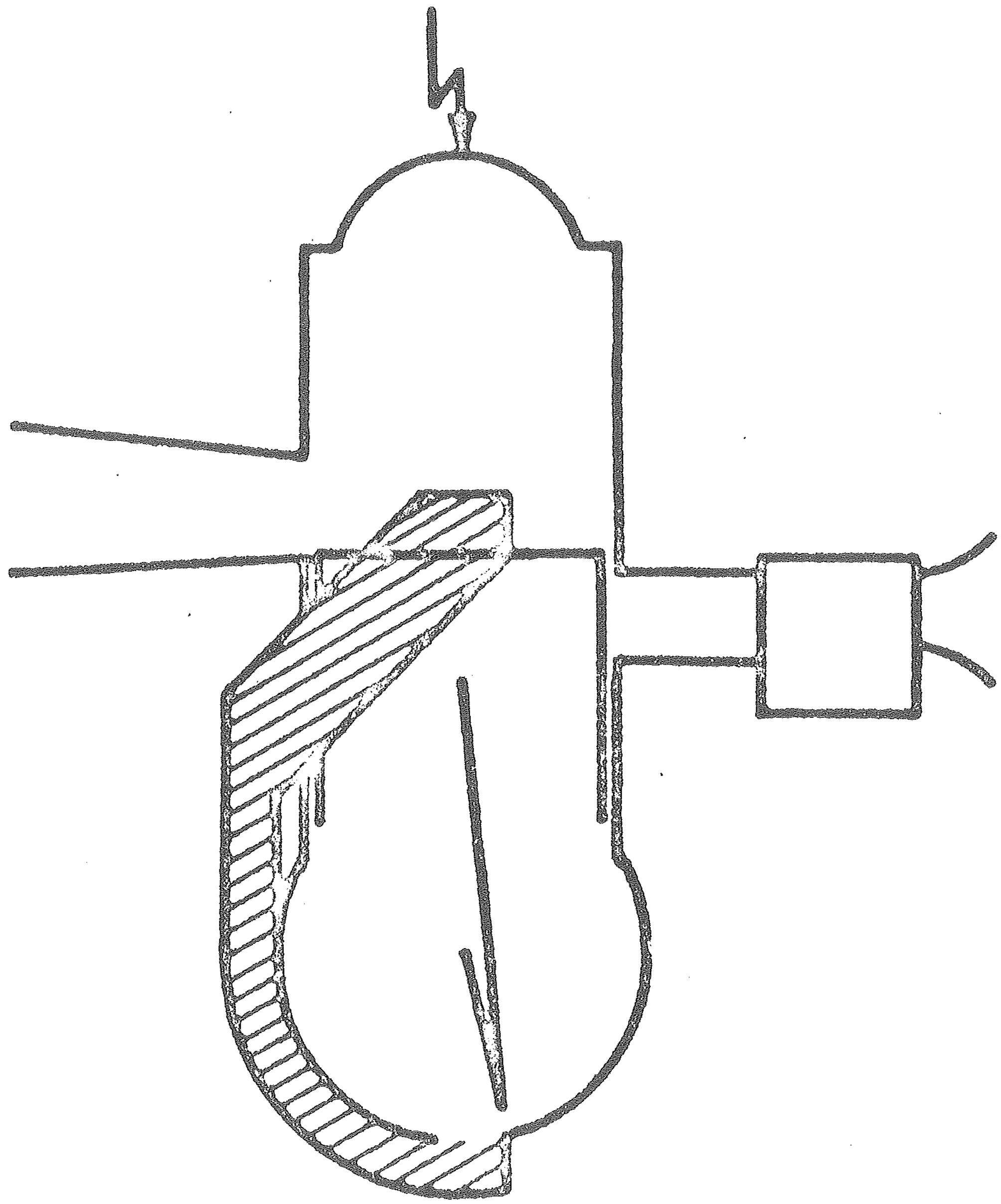

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Figure 18. EGR ignition system of S. Onishi (Ref. 59).

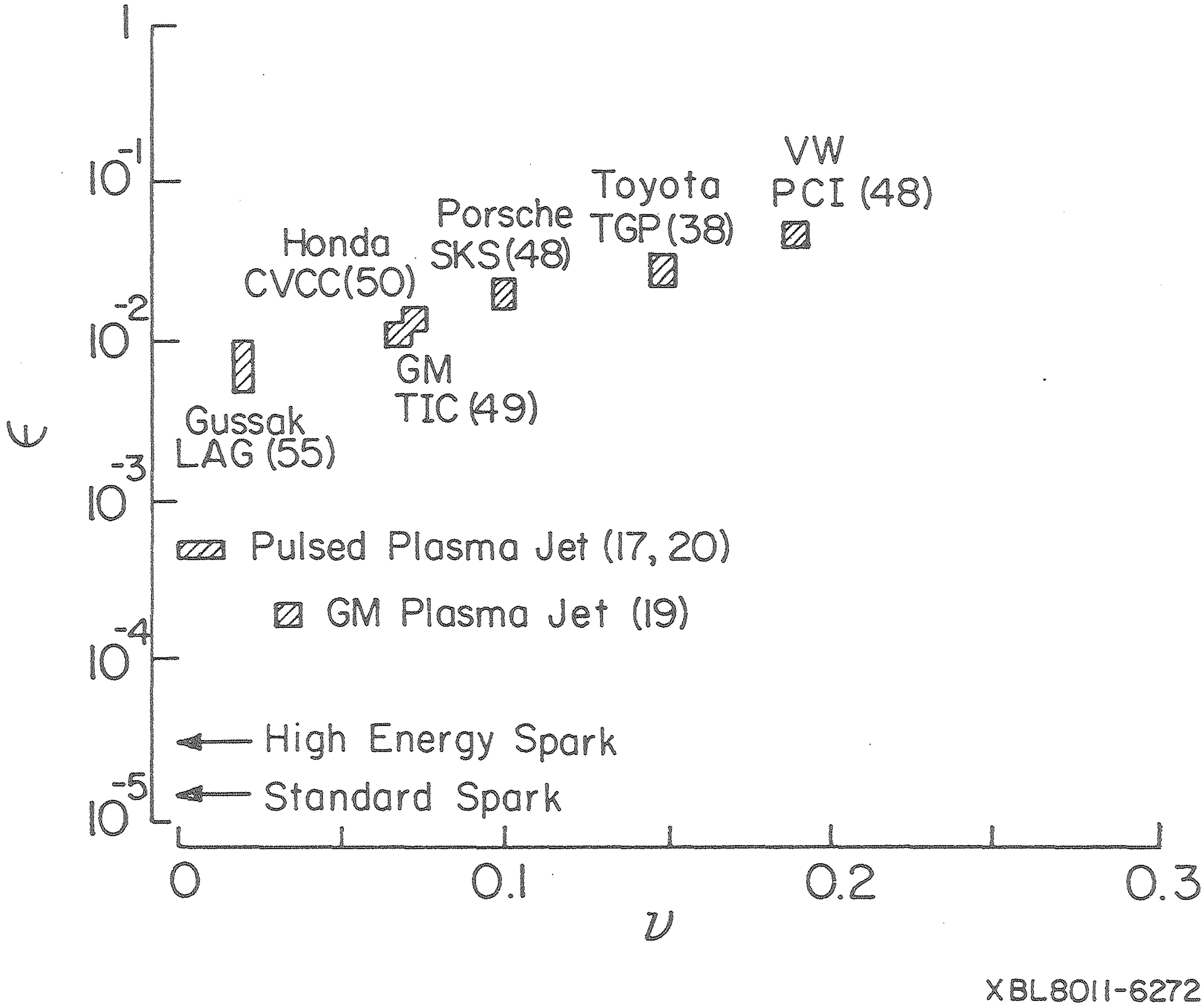

Figure 19. Distribution of ignition systems on the plane of relative volumes (ν) and energies (ε). Numbers in brackets designate References.